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Ecosystem Status and Trends Report for the Strait of Georgia Ecozone

Rapport de l'état des écosystèmes et des tendances pour l'écozone du détroit de Georgie

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ABSTRACT

The Strait of Georgia is a semi-enclosed sea located between Vancouver Island and mainland British Columbia. Water circulation in the Strait is dominated by estuarine exchange (out at the surface, in at depth) and by tidal and wind mixing. The Strait is highly productive, supporting commercial, aboriginal and recreational fisheries. It is also surrounded by a growing urban population, which is putting pressure on the ecosystem of the Strait. Global climate change acts locally through changes in seawater and river temperature, in the oxygen concentration and pH of inflowing deep water and in the timing of river discharge. Other changes have resulted from local human activities, such as shipping, fishing, discharge of contaminants and habitat destruction, including the construction of hard edges, which will interact with sea level rise. The ecosystem has shown resilience in the past, having recovered from numerous stressors and climatic variations. However, the combination of accelerating climate change with urbanization and fishing pressure is new. We do not know how the ecosystem will respond to the cumulative effects of human- and climate-driven changes in the future.

The Strait of Georgia is warming at all depths (1970-2006), while the concentration of oxygen in the deep water is decreasing. The Fraser River's summer temperature has increased (1942-2006), while its summer flow has decreased, resulting in increased pre-spawning mortality of Pacific salmon. Zooplankton abundance is decreasing in the Strait of Georgia, and the maximum biomass is peaking as much as 50 days earlier now than in the 1970s. These changes threaten the survival of some marine birds, and may threaten late-migrating juvenile salmon, but a directly attributable effect on planktivorous fishes has not been demonstrated. The populations of several piscivorous fishes (coho and Chinook salmon, ling cod, Pacific cod and inshore rockfish) have declined (1986-2006), while those of predominantly planktivorous fishes (chum and sockeye salmon, Pacific hake, spiny dogfish, walleye pollock) are relatively stable or within the normal range of historical variability (1981-2006). Resident killer whales are threatened because of contaminants, traffic and declining availability of prey (primarily Chinook salmon). The populations of all the pods were stable or increasing locally until the mid-1990s, when they all began to decline simultaneously, closely correlated with a coast-wide decline in the population of Chinook salmon. Since 2001 the killer whale population has increased again, though more gradually than it declined.

RÉSUMÉ

Le détroit de Georgie est une mer semi-fermée située entre l'île de Vancouver et la partie continentale de la Colombie-Britannique. La circulation de l'eau dans le détroit est dominée par un échange estuarien (eau de sortie en surface, eau d'entrée en profondeur) modulé par les marées et le vent. Le détroit est très productif, soutenant les pêches commerciales, autochtones et récréatives. Il est également entouré par une population urbaine en croissance, ce qui accroît la pression exercée sur l'écosystème du détroit. Les changements climatiques mondiaux s'observent localement par les changements de la température de l'eau de mer et du fleuve, par la concentration d'oxygène et le pH de l'arrivée d'eau en profondeur, et par la séquence du débit fluvial. D'autres changements sont attribuables aux activités anthropiques locales, par exemple, l'expédition, la pêche, le rejet de contaminants et la destruction d'habitats, y compris la construction de bords solides, ce qui interagira avec la hausse du niveau de la mer. L'écosystème a fait preuve de résilience par le passé, s'étant rétabli à la suite de plusieurs agents de stress et de variations climatiques. Toutefois, l'accélération des changements climatiques associée à l'urbanisation et à la pression exercée par les pêches est une situation nouvelle. Il n'est pas possible de prévoir comment réagira l'écosystème dans l'avenir aux effets cumulatifs des changements entraînés par les activités humaines et le réchauffement climatique.

Le détroit de Georgie se réchauffe à toutes les profondeurs (1970-2006), alors que la concentration d'oxygène diminue dans l'eau profonde. La température du fleuve Fraser a augmenté durant l'été (1942-2006), tandis que son débit durant l'été a diminué, ce qui se traduit par une augmentation de la mortalité prégénésique du saumon du Pacifique. L'abondance de zooplancton diminue dans le détroit de Georgie et il atteint sa biomasse maximale jusqu'à 50 jours plus tôt comparativement aux années 1970. Ces changements menacent la survie de certains oiseaux marins et ils risquent de constituer une menace pour les saumons juvéniles migrateurs tardifs, mais on n'a pas démontré un effet directement attribuable à ces changements sur les poissons planctonophages. Les populations de plusieurs poissons ichtyophages (saumon coho et quinnat, morue-lingue, morue du Pacifique et sébaste de la zone côtière) ont diminué (1986-2006), alors que les populations de poissons principalement planctonophages (saumon kéta et sockeye, merlu du Pacifique, aiguillat commun, goberge de l'Alaska) sont relativement stables ou se situent dans la fourchette normale de variabilité historique (1981-2006). Les épaulards résidents sont menacés en raison des contaminants, du trafic maritime et de la disponibilité en déclin des proies (principalement du saumon quinnat). Les populations de tous les groupes ont été stables ou ont augmenté localement jusqu'au milieu de 1990, alors qu'ils ont tous enregistré simultanément un déclin étroitement corrélé au déclin observé pour l'ensemble de la zone côtière de la population de saumon quinnat. Depuis 2001, la population d'épaulards a connu une augmentation à nouveau, quoique plus lente que le déclin qu'elle avait subi.

HIGHLIGHTS

1. The Strait of Georgia is warming at all depths (1970-2006), while the concentration of oxygen in the deep water is decreasing.

2. The Fraser River's summer temperature has increased (1942-2006), while its summer flow has decreased, resulting in increased pre-spawning mortality of Pacific salmon.

3. The abundance of *Neocalanus plumchrus*, formerly the most common zooplankter in the Strait of Georgia, is decreasing, and the maximum zooplankton biomass is peaking as much as 50 days earlier now than in the 1970s. These changes threaten the survival of some marine birds, and may threaten late-migrating juvenile salmon, but a directly attributable effect on planktivorous fishes has not been demonstrated.

4. The populations of several piscivorous fishes (coho and Chinook salmon, ling cod, Pacific cod and inshore rockfish) have declined (1986-2006), while those of predominantly planktivorous fishes (chum and sockeye salmon, Pacific hake, Pacific herring, spiny dogfish, walleye pollock) are relatively stable or within the normal range of historical variability (1981-2006).

5. The Southern and Northern populations of Resident killer whales are designated under *SARA* as Endangered and Threatened, respectively. Threats to their survival that have been identified include contaminants, disturbance by marine traffic and declining availability of prey (primarily Chinook salmon). The populations of all the pods were stable or increasing locally until the mid-1990s, when they all began to decline simultaneously, closely correlated with a coast-wide decline in the population of Chinook salmon. Since 2001 the resident killer whale populations have increased again, though more gradually than they declined.

DRIVERS OF CHANGE

Both climate change and human activities are changing the Strait of Georgia's ecosystem. Climate forcing can be unidirectional (global warming, sea level rise), cyclic on a yearly to decadal scale (El Niño Southern Oscillation, Pacific Decadal Oscillation), or episodic (storms, brief high river discharge events). Human pressures include fishing, shipping, habitat destruction, and the introduction of contaminants, invasive species and hatchery-reared fish. Climate and human-driven changes will interact with largely unknown effects. Of the changes observed and predicted to date, the increase in temperature, changed seasonal pattern in river discharge and degradation of coastal habitat will probably have the most profound effects on the marine ecosystem.

STATUS AND TRENDS INDICATORS

1. TEMPERATURE

Global air temperature is rising at an unprecedented rate (IPCC, 2007), and the effect is being felt locally. The annual average maximum and minimum air temperatures in British Columbia have increased significantly over the last 50 years (B.C., 2006). Seawater in the Strait of Georgia has also warmed over the last few decades (Figure 1). Although the Strait is up to 460 m deep in places, all the seawater that enters the basin must flow over a shallow sill. Consequently, from 1970 to 2006, the water at all depths of the Strait has been warming at the same rate (0.024°C/yr) as the uppermost 150 m of the open ocean (Masson and Cummins, 2007). El Niño conditions have caused further episodic warming of the water column (Masson and Cummins, 2007). These long-term and episodic warming events overlie a seasonal variation in seawater temperature of about 5°C in surface water (range 7.5 – 12.5°C) and 0.5°C at the bottom (range 8.5 – 9°C, Masson and Cummins, 2007). In seawater, even small changes in temperature are significant. The phytoplankton species assemblage in the Strait of Georgia has been very sensitive to variations in water temperature since the end of the last glaciation, with measurable changes in composition observed as a result of changes in temperature of only a few degrees (Hobson *et al.*, 2001). In contrast to temperature, salinity has shown no trend in recent decades (Diane Masson, personal communication, September 2009).

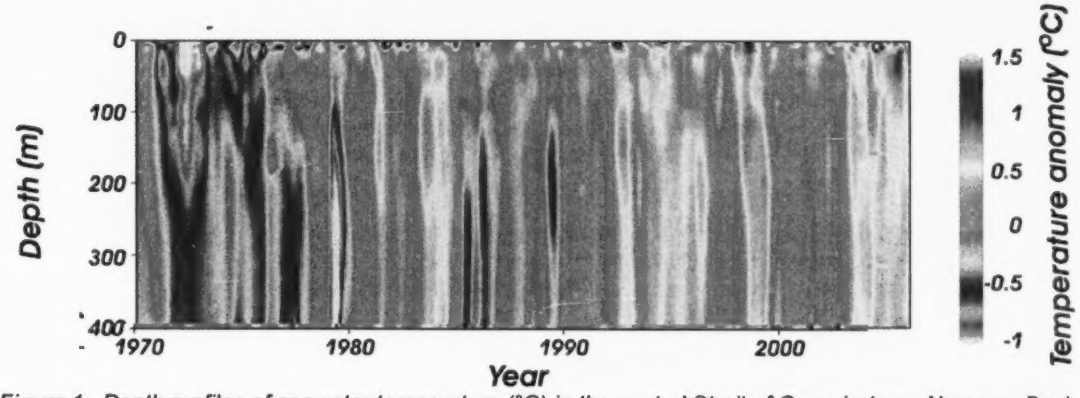

Figure 1. Depth profiles of seawater temperature (°C) in the central Strait of Georgia (near Nanoose Bay) since 1970. (from Masson and Cummins, 2007).

The temperature of major rivers draining into the Georgia Basin is also increasing. In the summer of 2006, nine new record high temperatures were set in the Fraser River (Figure 2). The summer temperature of the Fraser River is expected to rise by 1.9 °C by the end of the century. (Morrison *et al.*, 2002). A river temperature of over 21˚C prevents sockeye salmon (*Oncorhynchus nerka*) migration (Hyatt *et al.*, 2003), and high summer river temperatures can delay migration significantly, leading to greater pre-spawning mortality. A computer model of the Fraser River by Morrison *et al.* (2002) predicts that by the end of this century, the number of days when river temperature exceeds 20˚C will have increased tenfold, and that this threshold may be exceeded in other rivers as well. Increased seawater temperature can also favour certain invasive species and parasites, such as sea lice (*Lepeophtheirus salmonis*), that survive better and mature much more quickly under warmer conditions (Figure 3, Hevroy *et al.*, 2007). For example, McPhail (2007) indicated that increased temperatures in the Fraser River could assist the establishment of a population of the non-native, planktivorous American shad (*Alosa sapidissima*) in the river that could compete for food with juvenile salmon.

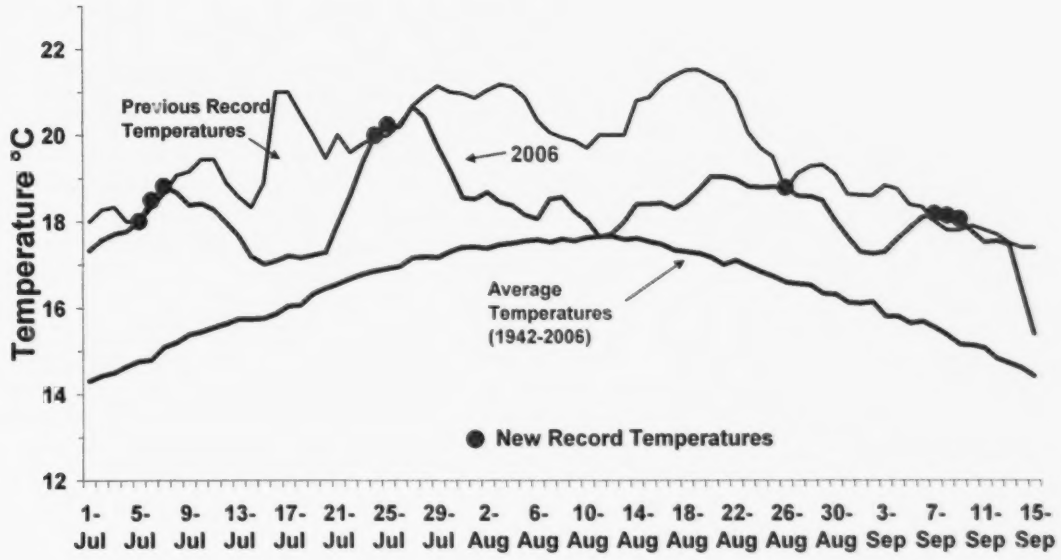

Figure 2. The Fraser River is warming in the summer. In the summer of 2006, new record temperatures were set on 9 days. (modified from Morrison, 2006 in DFO, 2007)

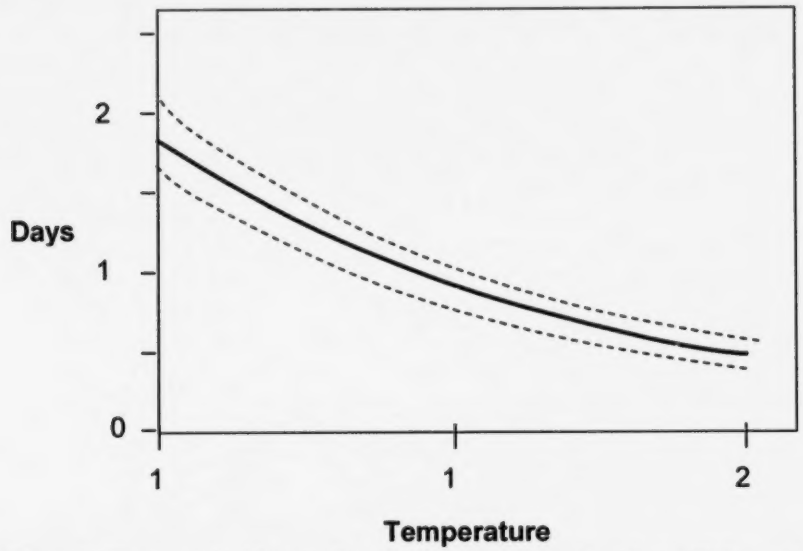

Figure 3. Time required for sea lice attached to an Atlantic salmon (Salmo salar) to moult from the copepodite to chalimus II stage as a function of temperature. Sea lice can reproduce about twice as fast at 20°C as at 15°C. (Modified from Hevroy, 2007).

The increased air temperature also affects the timing of river discharge. Warmer weather will mean that, from November to April, more precipitation will fall as rain and less as snow (Whitfield *et al.*, 2003), so that less will be stored in the mountains to support the summer freshet.

2. FRESHWATER DISCHARGE / PRECIPITATION AND SEA LEVEL RISE

Rivers flow into the Strait of Georgia, driving the surface water seaward and drawing in a return flow of seawater at depth. The river discharge is strongly seasonal: the snow-fed rivers, including the Fraser River, peak in the early summer, while the much smaller, rain-fed rivers of Vancouver Island peak in the winter. Fresh water from the rivers stabilizes the water column, allowing phytoplankton to remain near the surface where there is enough light for them to grow. However, the stability produced by the fresh water can also reduce the mixing of nutrient-rich, deep water to the surface. Consequently, the stability that allows a phytoplankton bloom to develop also prevents the resupply of nutrients to that bloom.

The Fraser River's discharge pattern is changing. In recent decades the summer peak flow has decreased, while the winter flow has increased, and the late spring freshet is arriving earlier (Morrison *et al.*, 2002). The date by which one half or one third of the total annual flow is reached has become earlier over the last 100 years (Figure 4). (The date of the actual peak flow is not plotted, because that date can be affected by a single large rainstorm; John Morrison, personal communication, 2008.) The observed changes are projected to continue throughout this century, as the discharge changes from a snowmelt-dominated to a rainfall-dominated pattern (Figure 5). Morrison et al. (2002) predict that by 2080 the peak flow will be significantly lower than today's and will usually occur about 24 days earlier than the average for 1961-1990, although it will also become more variable.

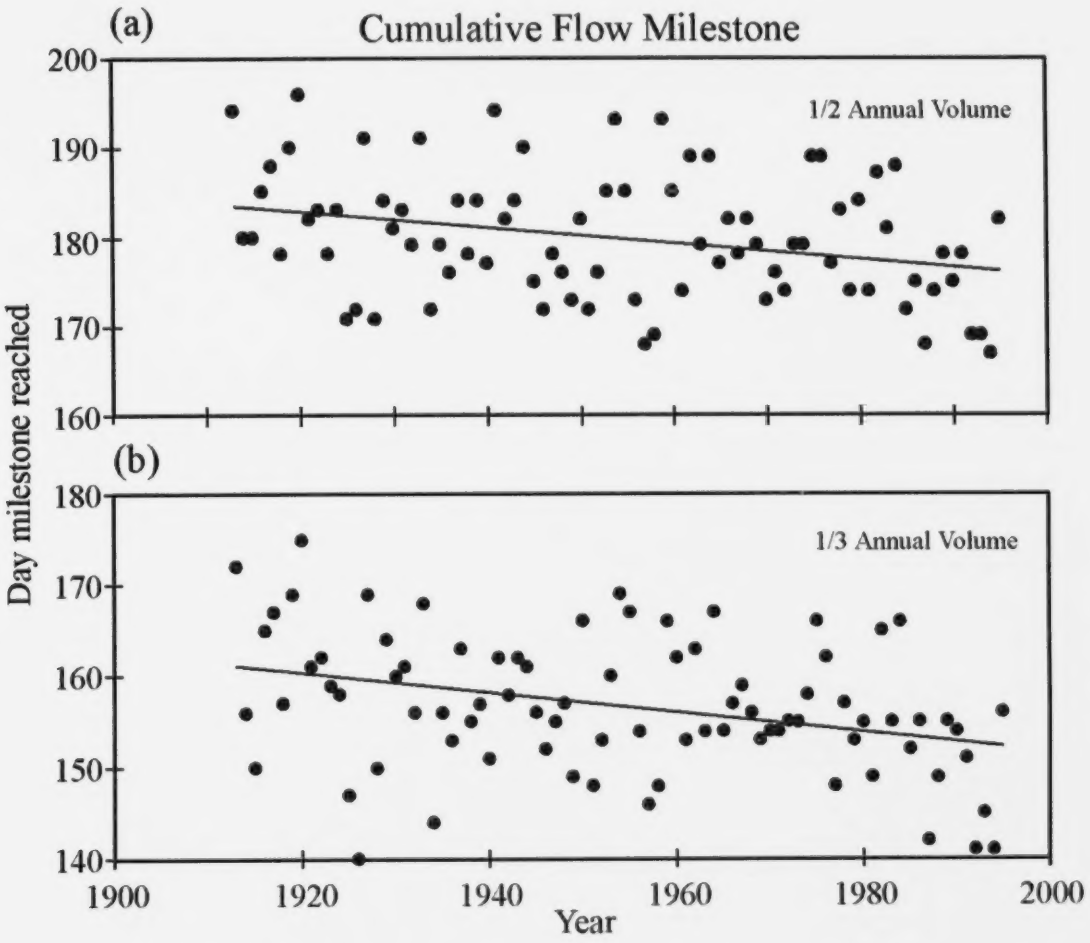

Figure 4. Date by which (a) one half and (b) one third of the cumulative Fraser River flow for a given year is reached. Figure from Morrison et al. (2002).

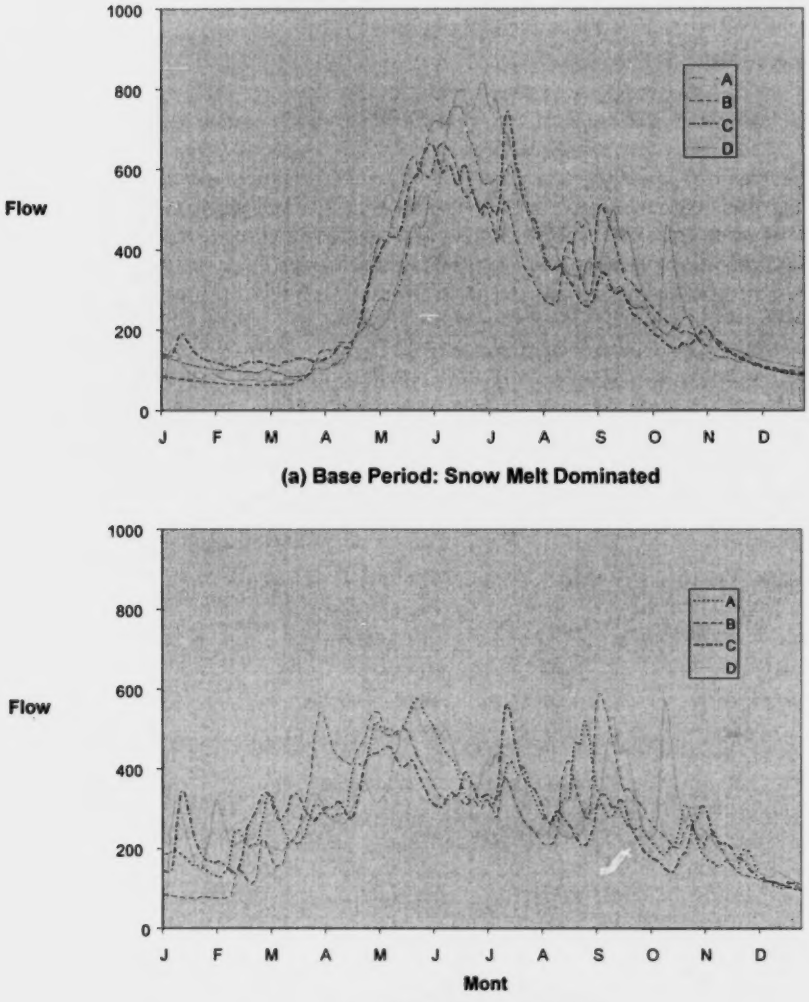

Figure 5. Modelled daily Fraser River discharge (m^3/s) under (a) current, snowmelt-dominated and (b) projected rainfall-dominated conditions. The four lines (A-D) represent the discharge from four rainfall-dominated years during the base period projected forward 110 years (modified from Morrison et al., 2002).

In addition to the trend toward an earlier, smaller freshet, river flow may be more variable day-to-day in the near future. The late spring, short-term (< 6 hour) precipitation intensity has increased over the last 10 years in the Vancouver area, probably as a result of the recent Pacific Decadal Oscillation warm phase in combination with a contribution from El Niño events (Jakob *et al.*, 2003). At present the inter-decadal variability in short-term discharge outweighs the gradual trend that can be ascribed to climate change (Jakob *et al.*, 2003). Changes in river

discharge associated with short-term events can affect phytoplankton productivity in the Strait (Yin *et al.*, 1997a).

Since the end of the last glaciation 12000 – 10000 years ago, sea level has changed dramatically in the Strait of Georgia. When the ice first melted, sea level increased rapidly, reaching a highstand of 50-200 m (varying with location) above the present day level (Barrie and Conway, 2002). Then the crust rebounded from its depression by the weight of the ice, lowering the relative sea level. The rebound of the crust in the southern Strait of Georgia is recorded in local First Nations oral history in a story about the emergence of the Saanich Peninsula – in the Coast Salish language, "Saanich" (W̱SÁNEĆ) means "raised" or "emerged" (Paul *et al.*, 1995). The post-glacial rebound, which raises the land relative to the ocean, has now slowed to about 0.25 mm/yr in the Strait of Georgia (Thomson *et al.*, 2008). However, the movement of continental and oceanic plates off Vancouver Island is causing an uplift of land at about ten times that rate, a rate comparable to that of the global increase in water volume due to thermal expansion of sea water and increased meltwater from glaciers (Thomson *et al.*, 2008). In the Strait of Georgia the Fraser Delta is subsiding (compacting and sinking) at about 1-2 mm/yr. Together these processes are expected to result in an increase in local sea level between the years 2007 and 2100 of 35 cm for the whole Strait of Georgia and 55 cm over the Fraser Delta (Thomson *et al.*, 2008).

3. WATER CHEMISTRY (OXYGEN, NUTRIENTS, CARBON AND PH)

At the surface of the Strait of Georgia, oxygen (O_2) is produced by phytoplankton and also diffuses and mixes into the seawater from the atmosphere. At depth O_2 is periodically re-supplied by deep water renewal in the late spring and late summer, combined with mixing in Haro Strait (Masson, 2002). Oxygen is consumed during the breakdown of organic matter in the water column and sediments. In the early spring the concentration of oxygen in the deep, central Strait can be as low as 2 mL/L (Masson and Cummins, 2007), less than a quarter of that measured at the surface. The deep Strait of Georgia has not been anoxic (without oxygen) in recorded history, but the oxygen concentration in the deep water has decreased by 0.02-0.03 mL/L per year over 1970-2006 (Diane Masson, personal communication, 2009). Although a quarter of this decrease could be explained by a decrease in solubility due to the warming of the seawater, the majority of the change requires another explanation. A similar decrease in the subsurface oxygen concentration in the subarctic Pacific Ocean has been explained as the result of reduced winter ventilation along the Asian coast, which decreases the flux of the oxygen into the intermediate ocean (Whitney *et al.*, 2007). Elsewhere the decrease has been ascribed to increased stratification of the warming surface water (e.g.Matear, 2006). In the Strait of Georgia, this process does not apply directly, because stratification in the Strait is driven by salinity, rather than by temperature, and the salinity has not changed appreciably over the history of measurements (Diane Masson, personal communication, September 2009). Rather, it is possible that the reduction of oxygen in the deep waters of the Strait is the result of lower oxygen levels in waters off the BC continental slope. The oxygen in the deep basins of the Strait of Georgia is mainly replenished by episodic deep water renewal, so if the deep water outside the Strait is becoming increasingly depleted in oxygen (a decline of as much as 1.3%/yr has been observed in waters 150 to 500 m deep over the past 25 years; Frank Whitney, unpublished data, 2009) , then the water that flows into the deep basins during deep water renewal will contain progressively less oxygen with time.

The nitrogenous nutrients required for phytoplankton growth enter the Strait of Georgia principally from the Pacific Ocean via coastal upwelling and estuarine inflow (Mackas and Harrison, 1997), although there are also small contributions from river discharge, agricultural

runoff and sewage. The nutrients in the inflowing, deep water are entrained into the surface layer by mixing with surface water in Haro Strait and around the plume of the Fraser River (Yin *et al.*, 1996). Nutrient concentrations in the surface water can change rapidly (over a time scale of days) in response to wind-mixing by storms, brief variations in the Fraser River's discharge, variations in tidal flow and uptake by phytoplankton. No trend in nutrient concentrations has been observed over the period of recent monitoring (2002-2006) (Peña, 2006, in DFO, 2007).

Organic carbon enters the Strait of Georgia in two main ways: phytoplankton production and river discharge (e.g. Johannessen *et al.*, 2003). Many contaminants adhere to and are transported with organic carbon, either into the bottom sediments or into the food chain. When organic carbon is oxidized, it can change the nature of the contaminants, transforming them into products of either higher or lower toxicity. About a quarter of the organic carbon that passes through the Strait of Georgia each year is oxidized in the water column or in sediments of the Strait (Johannessen *et al.*, 2008b). The oxidized carbon may sustain microbial ecosystems or undergo chemical / photochemical reactions, but these processes have not been quantified locally. Organic carbon trends in the water column of the Strait of Georgia are largely unknown, because very few measurements have been made.

There is no Strait of Georgia pH time series from which to assess trends in pH or to look for acidification, although measurements are now under way. It is likely that pH is declining in the deep basins (Johannessen and Macdonald, 2009). Similarly to the process proposed above to explain the declining concentration of oxygen, the deep water of the Strait of Georgia is replenished by seasonal intrusions of upwelled Pacific Ocean water, which is becoming significantly more acidic (Feely *et al.*, 2008). Decreased pH in the deep basins has the potential to harm benthic organisms which cannot move and to reduce the extent of the habitat available to those that can, and may have the greatest impact on organisms producing calcareous exoskeletons. There are no data available that would allow the assessment of the effect of changing pH on the Strait of Georgia benthos.

4. PRIMARY PRODUCTION

Primary production by phytoplankton supports the food chain. Quantifying productivity in the Strait of Georgia has been controversial (e.g. Harrison *et al.*, 1983; Parsons *et al.*, 1980), but all authors agree that it is high (120 - 345 gC m^{-2} yr^{-1}). The difficulty in determining total productivity stems in part from the extreme patchiness of the phytoplankton distribution. Productivity is highest at fronts, where different water masses meet (e.g. Harrison *et al.*, 1983; Parsons *et al.*, 1980). There are fronts around the edges of the Fraser River plume and where the high energy environments of Discovery Passage (Haro Strait) and Johnstone Strait meet the Strait of Georgia. In addition to the spring bloom, the Strait of Georgia often sees intermittent blooms lasting a few days each, throughout the spring and summer (A. Peña, Fisheries and Oceans Canada, unpublished data; J. Gower, Fisheries and Oceans Canada, unpublished data; Figure 6).

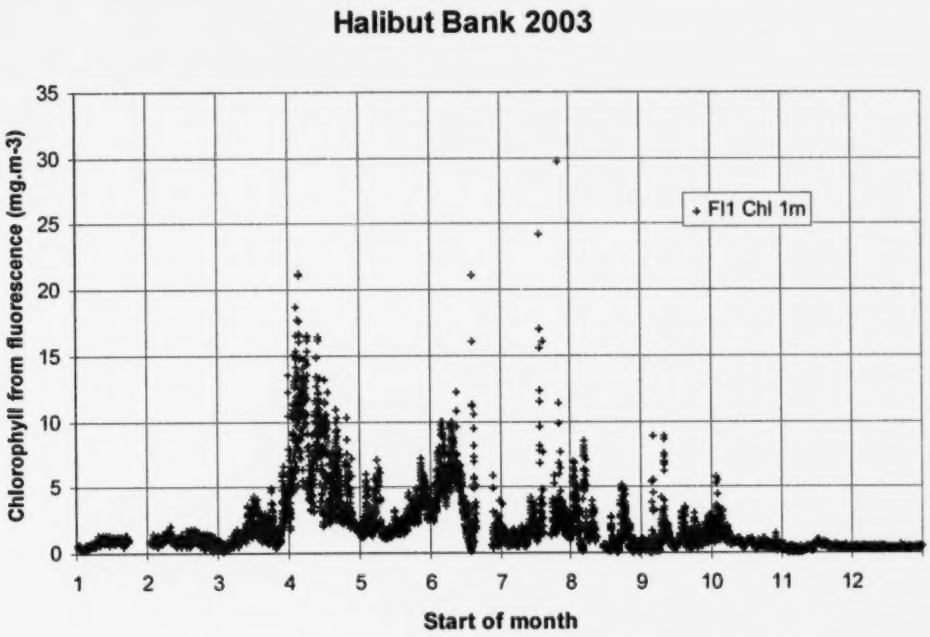

Figure 6. Surface chlorophyll fluorescence in the south-central Strait of Georgia (Halibut Bank) in 2003 (J. Gower, Fisheries and Oceans Canada, unpublished data). The spikes in chlorophyll fluorescence represent phytoplankton blooms. In 2003 the largest blooms occurred in April and June, but there is considerable interannual variability in the timing and magnitude of the blooms (A. Peña, Fisheries and Oceans Canada, unpublished data).

It is not yet possible to determine trends in total productivity over time because of limited survey coverage (repeated, comprehensive surveys began in 2002) and the difficulty of estimating total primary productivity. It has been suggested that an earlier spring phytoplankton bloom might explain the observed change in the timing of the peak zooplankton biomass (see below), but we lack observations to confirm such a trend in the phytoplankton.

5. SECONDARY PRODUCTION (ZOOPLANKTON)

Zooplankton consume phytoplankton and transfer the energy fixed in primary production to the rest of the food chain. They are a major food source for larval fish, marine birds and other organisms (Pauly *et al.*, 1996). Zooplankton aggregate where and when there is food available, at fronts, for example, in the Strait of Georgia. The high concentration of zooplankton in and around the marine and estuarine plumes of the Fraser River may explain the extended residence time of juvenile salmon and herring in rearing areas adjacent to these plumes (St. John *et al.*, 1992). The biomass of *Neocalanus plumchrus*, until recently the dominant zooplankter in the Strait, has decreased sharply in recent years (El-Sabaawi *et al.*, 2009 and Figure 7). The total zooplankton population also appears to be declining (R. El-Sabaawi and J. Dower, University of Victoria unpublished data), although more data are required to determine how quickly the decline is taking place and whether the current trend will continue.

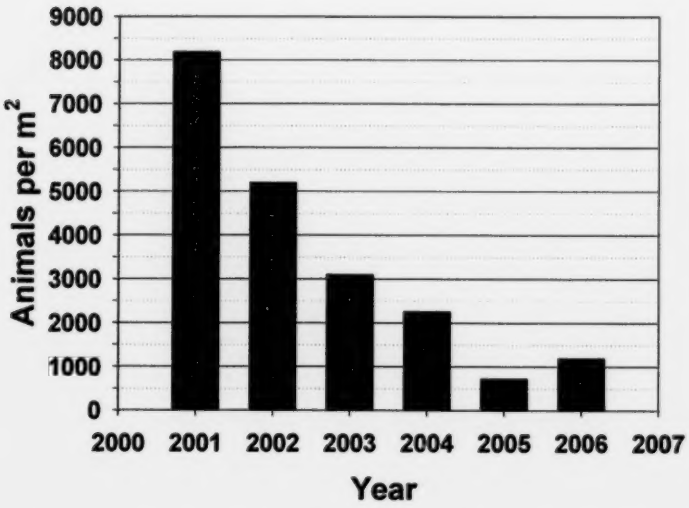

Figure 7. Recent decline in the population of Neocalanus plumchrus in the Strait of Georgia (El-Sabaawi et al., 2009).

The timing of the peak zooplankton biomass is changing rapidly. *Neocalanus plumchrus* now reaches its peak biomass about two months earlier than it did in the mid-1960s (Figure 8). The cause of the change is unclear, since the phytoplankton bloom does not show such a consistent trend. Possibly the zooplankton bloom is triggered by water temperature, instead of by the presence of food. Gardner (1977) showed that the populations and species assemblage of overwintering zooplankton in the Strait of Georgia were strongly correlated with the water temperature and stability of the preceding August and September, even more strongly than with similar hydrographic conditions during the spring reproductive season. He cautioned, however, that the physical variables themselves might not be the direct cause of the changes in zooplankton communities, but might rather be proxies for changes in chemical composition, including variations in organic carbon, nutrients and trace metals.

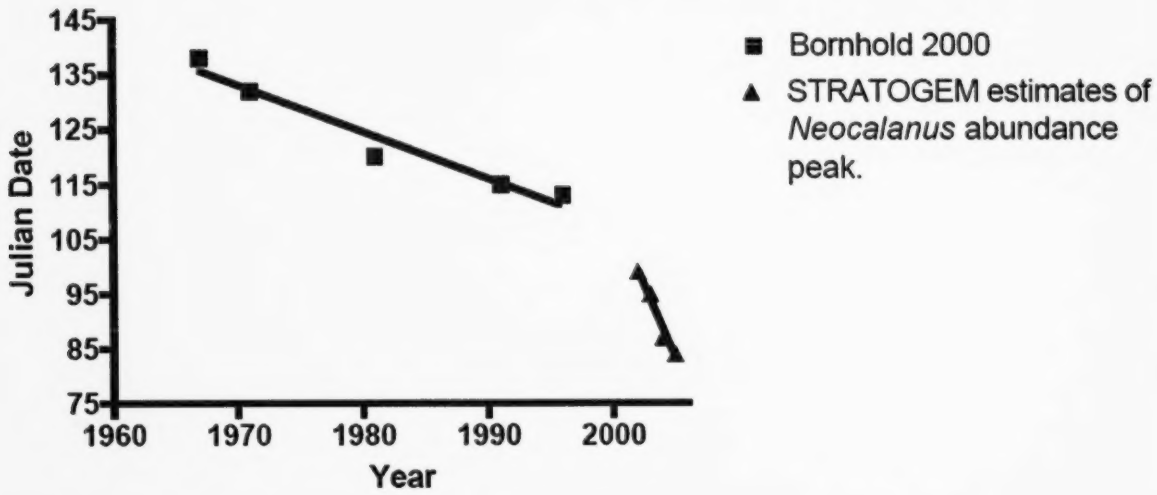

Figure 8. Temporal trend in the timing of peak Neocalanus plumchrus biomass in the Strait of Georgia. Bornhold data (squares) are from back-calculation of the timing of the Neocalanus peak. The STRATOGEM data (2002-2005) are based on direct observations of Neocalanus stage composition in the Strait of Georgia. The suggestion, still preliminary, is that the shift in Neocalanus timing may be accelerating. (Figure and interpretation by R. El-Sabaawi and J. Dower, University of Victoria, unpublished data).

5.1 Timing mismatch between juvenile fish and their prey

Outmigrating salmon smolts require a large and readily-available food supply in the spring as the young fish enter and adapt to the ocean environment. Recent work has shown that a mismatch can occur (Figure 9) between the timing of the zooplankton biomass peak and the presence or abundance of juvenile fish and other predators (e.g. seabirds, seals, seal lions and other fish) (Bertram *et al.*, 2001; Yin *et al.*, 1997b).

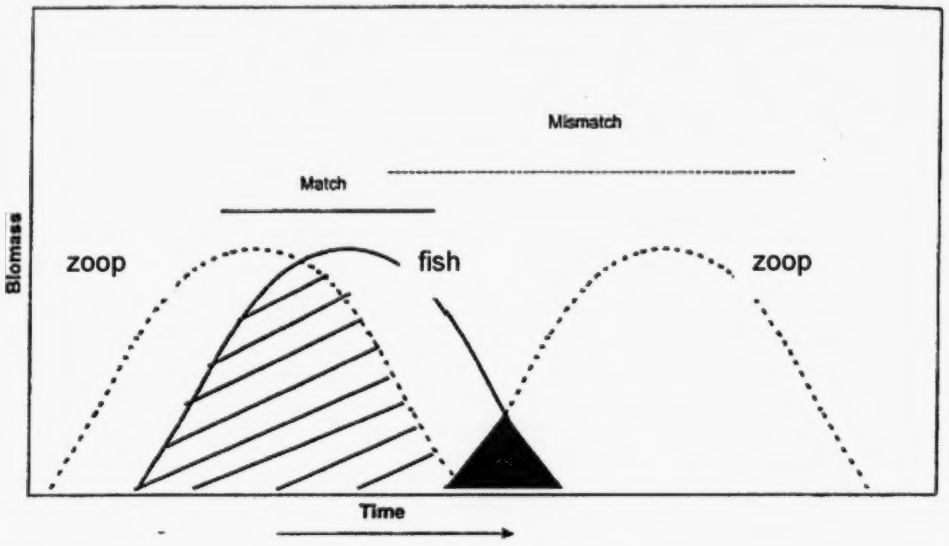

Figure 9. Schematic showing differing degrees of overlap between predators and prey that can result in a timing match or mismatch. (Modified from Bornhold, 2000. The original figure showed the potential match / mismatch between zooplankton and phytoplankton, but it applies equally well to juvenile fish and zooplankton.)

As the zooplankton biomass peak occurs earlier in the season (see Zooplankton section), populations of chum (*Oncorhynchus keta*), pink (*Oncorhynchus gorbuscha*) and some stocks of sockeye salmon (*Oncorhynchus nerka*), which enter the Strait earlier, have increased, while Chinook (*Oncorhynchus tschawytscha*) and coho (*Oncorhynchus kisutch*) populations have declined (e.g. Beamish *et al.*, 2004; Beamish *et al.*, 1995; King and Beamish, 2000). Strait of Georgia coho are now dominated by hatchery-reared fish (Figure 10), which are released in late spring. It has recently been proposed (Beamish *et al.*, 2006) that hatcheries should attempt to release fish earlier in those years when the freshet is expected to arrive early.

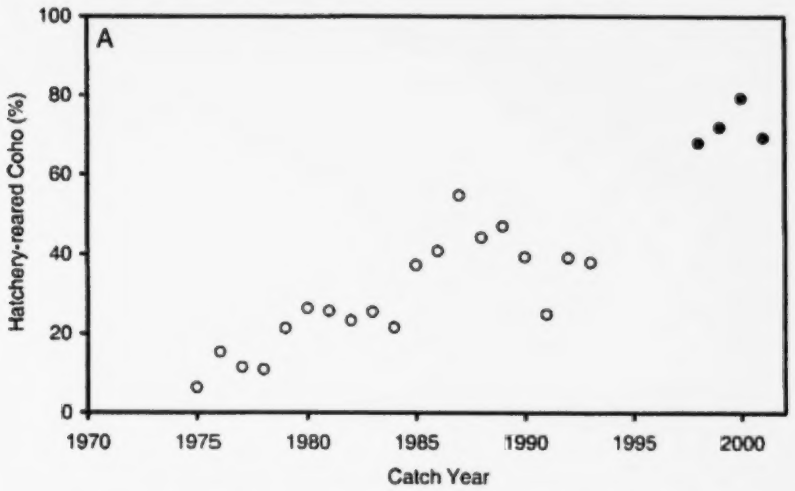

Figure 10. Percentage of coho in the Strait of Georgia that were hatchery-reared (1975 - 2000). Open circles represent data collected from sport and commercial catches; filled circles, data from research cruises (Sweeting et al., 2003).

6. PISCIVOROUS FISHES

There have been significant changes in the populations of some predominantly piscivorous (fish-eating) fish in recent decades. Coho (Figure 11, Beamish *et al.*, 2004; Simpson *et al.*, 2001) and Chinook salmon (Bailey *et al.*, 2001; Beamish *et al.*, 1995), lingcod (Ophiodon elongatus, King, 2005), Pacific cod (Gadus macrocephalus, Wallace, 2002) and some inshore rockfishes (yelloweye (Sebastes ruberrimus), quillback (Sebastes maliger), copper (Sebastes caurinus), black (Sebastes melanops), tiger (Sebastes nigrocinctus), and china (Sebastes nebulosus), Yamanaka and Lacko, 2001) have experienced population declines, as reflected in landings data (Figure 12a show these inshore rockfish landings; Figure 12b lingcod landings). In contrast, populations of pink and chum salmon, which are predominantly planktivorous, have increased. Non-migratory or resident piscivorous fish species (e.g. reef dwellers) appear to have been the most vulnerable to population declines, followed by inshore, semi-residents and lastly, by seasonal, rearing/migratory species. This is likely due to the year-round exposure of resident fish to predators, such as seals, seabirds, other fish and humans, and to contaminants and other nearshore effects of urbanization.

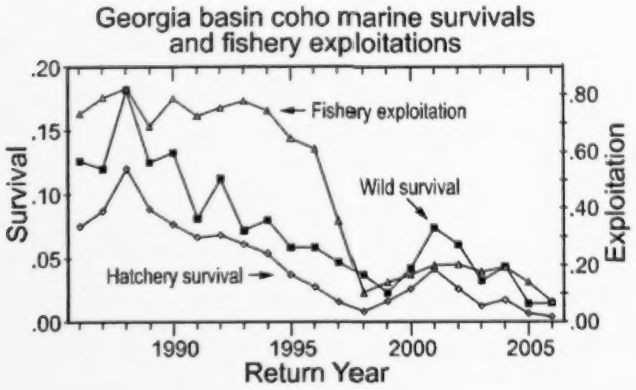

Figure 11. Georgia Basin marine coho survivals (proportion of outmigrating smolt population that returns in spawning year) and fishery exploitation. Modified from Simpson et al. (2001).

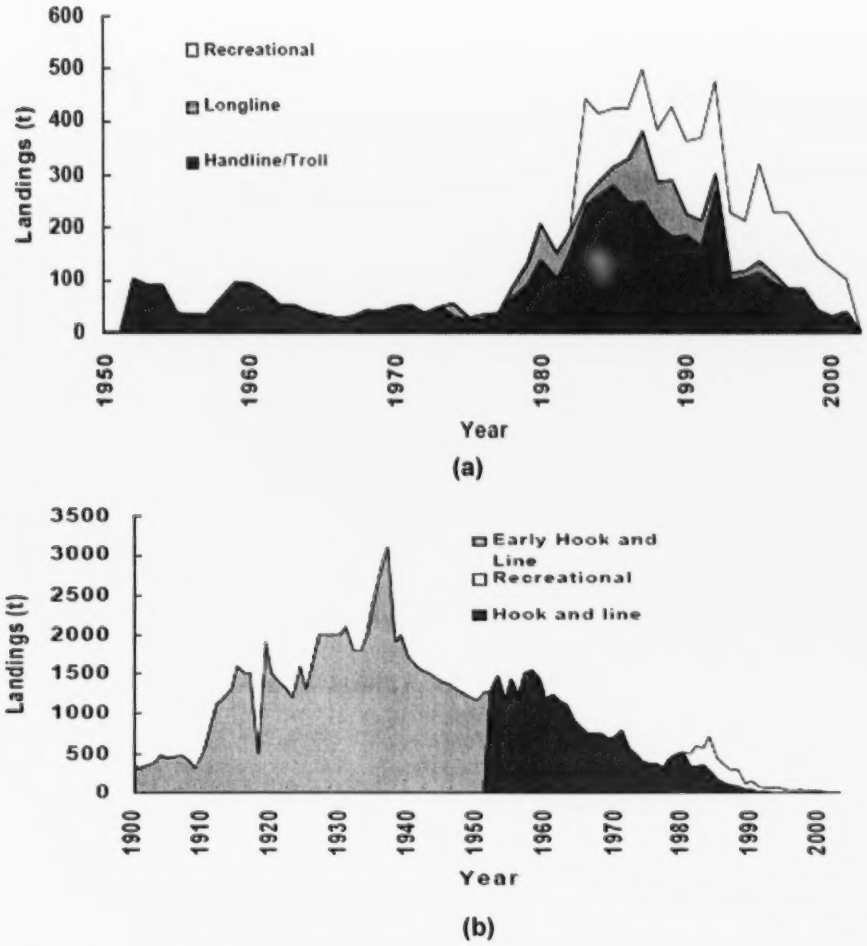

Figure 12. (a) Strait of Georgia inshore rockfish landings in the recreational, long-line and hand-line fisheries from 1954 – 2000. The increase in the 1980s is due to regulatory changes that increased the number of rockfish varieties that could be sold. (b) Commercial and recreational landings of lingcod in the Strait of Georgia from 1900 to 2000 (Wallace, 2002).

Over the last century, bottom trawl and hook and line fisheries have contributed to serial depletions of several inshore, piscivorous, bottom and pelagic fish species inhabiting the Strait of Georgia. Other contributors to population declines of piscivorous fish include the loss of spawning and rearing habitat, contaminants and environmental influences, such as large-scale oceanographic regime shifts, increased seawater temperatures and possibly declines and changes in prey populations (e.g. Labelle, 2009). The cumulative effect of all of these factors may test the resilience of these fishes.

7. PLANKTIVOROUS FISHES

Although the large salmon runs that pass through the Strait of Georgia receive the most public attention, it is the smaller, planktivorous fish, particularly Pacific hake (*Merluccius productus*) and Pacific herring (*Clupea pallasi*), that comprise the predominant fish species in the Strait of Georgia (Beamish and McFarlane, 1999). This has been the case throughout the Holocene (time since the end of the last glaciation, ~10,000 years ago) (Tunnicliffe *et al.*, 2001). Hake, herring, walleye pollock (*Theragra chalcogramma*) and juvenile spiny dogfish (*Squalus acanthias*) are influenced by many of the same environmental factors as are the piscivorous fishes, except that their prey is predominantly zooplankton, rather than other fish or invertebrates. Only larger and older hake and dogfish eat significant amounts of fish and other prey.

Biomass estimates of hake (~85-120 kt determined during the 1981 to 1996 period and 60 kt more recently), herring (~60-70 kt estimated in 2007), spiny dogfish (~ 60 kt) and walleye pollock (10-15 kt) have been relatively stable, although Pacific herring has experienced a sudden decline from a 130 kt peak in 2003. There are also some indications of a decline in the size at age among several of the predominant fish species, particularly hake and herring. (See hake and herring sections, below.)

7.1 Pacific Hake

A trawl fishery for the small, planktivorous, hake residing in the Strait of Georgia began in 1981. Hydroacoustic, midwater trawl and ichthyoplankton (fish egg and larvae) stock assessment surveys have been conducted periodically in the Strait of Georgia since 1981. These surveys have suggested a relatively stable biomass of 60,000-120,000 tonnes (Saunders and McFarlane, 1999). The 1995 peak in the Strait of Georgia hake fishery (Figure 13) was accompanied by a sharp decline in the size at age of the catch; improved year-class success in the 1990s is thought to have induced a density-dependent reduction in growth (King and McFarlane, 2006). Fish growth remained suppressed after the decline in the fishery in 2004 (King and McFarlane, 2006).

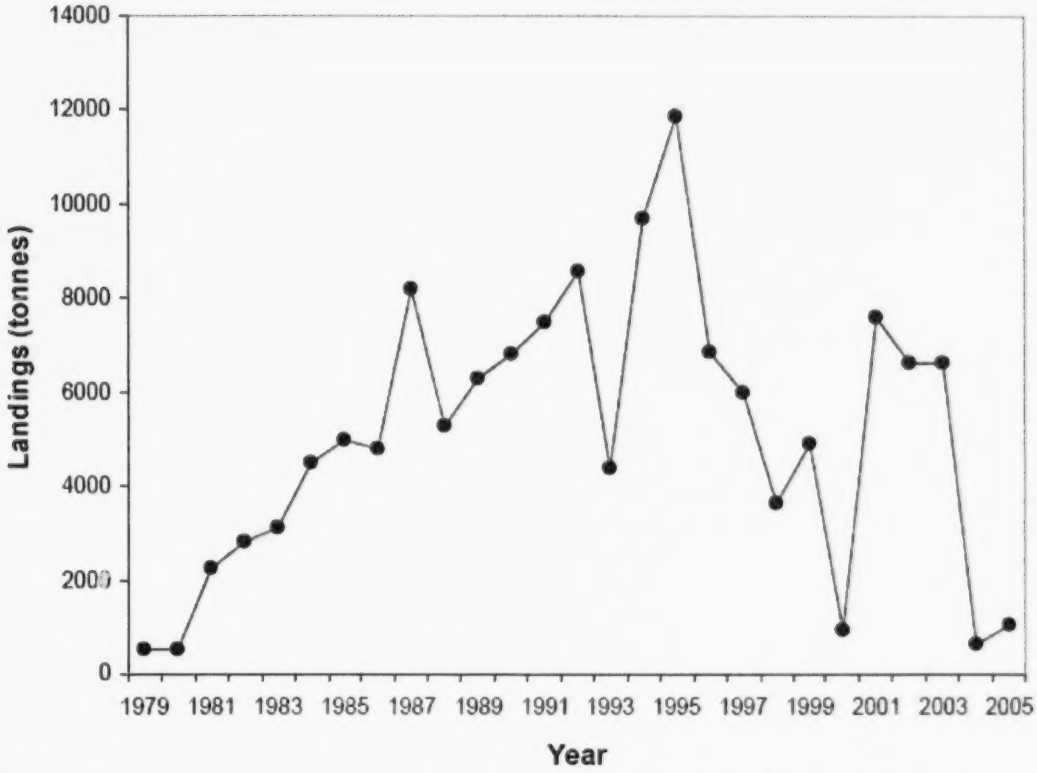

Figure 13. Annual landings (tonnes) of Pacific Hake captured in the Strait of Georgia (King and McFarlane, 2006).

7.2 Pacific Herring

Herring and other small, short-lived pelagic fishes are known for their dramatic fluctuations in abundance resulting from recruitment failures or unusually strong year classes (Figure 14, Schweigert and Haist, 2007). Climatic and habitat changes, contaminants, redistribution and abundance of predators and timing mismatches between juvenile fish and their prey (zooplankton) are some of the factors that influence recruitment. Intensive herring fishing during years of poor recruitment has led to fishery collapses and closures (e.g. high catches during the 1950s and early 1960s were followed by a coast-wide closure from 1968 to 1971, Schweigert and Haist, 2007).

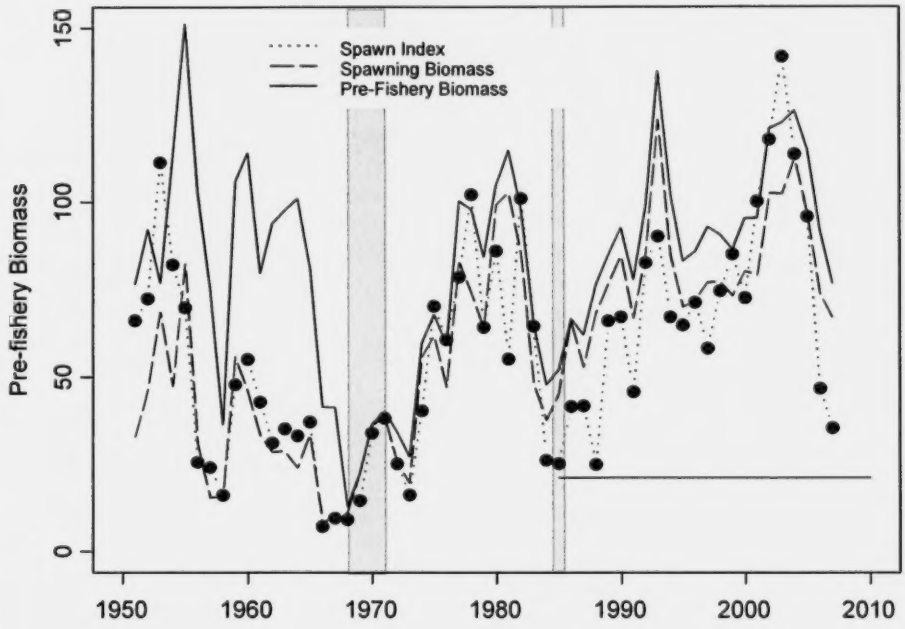

Figure 14. Spawning and pre-fishery biomass estimates (10^3 tonnes) and annual spawn indices for Pacific herring in the Strait of Georgia (Schweigert and Haist, 2007). The grey bars indicate the fishery closures of 1968-1971 and 1986, showing that, each time, the herring population began to recover once the fishing pressure was relieved. The horizontal line indicates the cut-off level which, if passed, results in a fishery closure.

Most Strait of Georgia herring feed off the west coast of Vancouver Island during the summer months. Annual Pacific herring spawning migrations that occur between October and March in the Strait of Georgia have increased significantly since the 1968-1971 fishery collapse and coast-wide closure (Schweigert and Haist, 2007). After a period of rapid rebuilding, the herring population in the Strait of Georgia declined briefly, and a one-year fishery closure occurred in 1986 (Schweigert, 2005). The herring population continued to increase in the subsequent years, peaking in 2004. Recently, the abundance of both inshore spawners (Schweigert and Haist, 2007) and inshore rearing juveniles has declined (T. Therriault, Fisheries and Oceans Canada, unpublished data, and Hay *et al.*, 2003). Because herring frequently undergo large swings in population, it is not clear whether the current decline is part of a short-term cycle that will soon be reversed, or whether it represents the beginning of a longer downward trend. There has also been a gradual decline in the size at age of Pacific herring in the Strait of Georgia as well as in other BC regions (Figure 15, Schweigert and Haist, 2007).

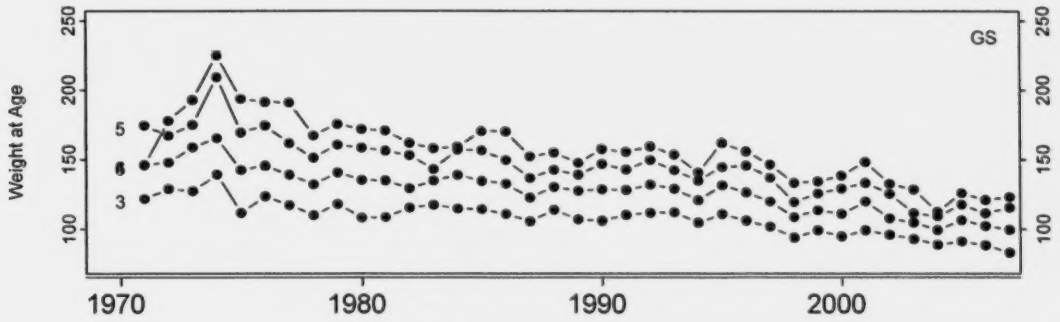

Figure 15. Estimates of weight-at-age (g) for 3-6 year old herring from 1970 to 2008 (Schweigert and Haist, 2007).

7.3 Fraser River eulachon

Some local fish populations show clear evidence of decline. The Fraser River eulachon population declined for at least a decade, beginning in the early 1990s (Figure 16) or possibly earlier. Since 2004 this population has stabilized at a minimal level, as measured by annual ichthyoplankton surveys (Therriault and McCarter, 2005).

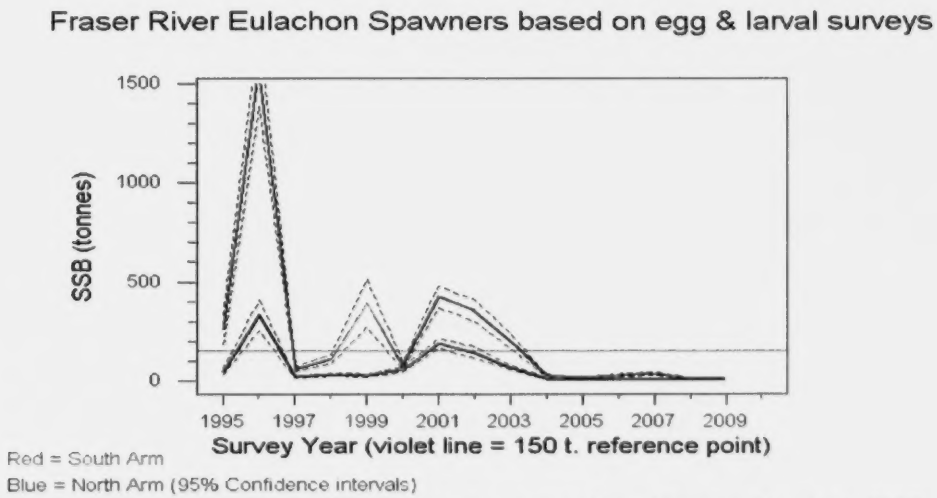

Figure 16. Fraser River eulachon spawners based on egg and larval surveys (Hay et al., 2002), extended by Bruce McCarter, unpublished data, 2009).

8. MARINE MAMMALS

The population of resident harbour seals (*Phoca vitulina*) in the Strait of Georgia has stabilized over the past decade (DFO, 2009; Olesiuk, 1999), following a tenfold increase between 1973 and 1997. The population grew at a rate of 11-12 % per year during the 1970s and 1980s, before slowing in the 1990s and then apparently stabilizing (Figure 17 and DFO, 2009). Long-

term recovery has been attributed principally to the end of predator control programs in 1970 and a moratorium on seal and sea lion hunting in 1972 (Olesiuk, 1999).

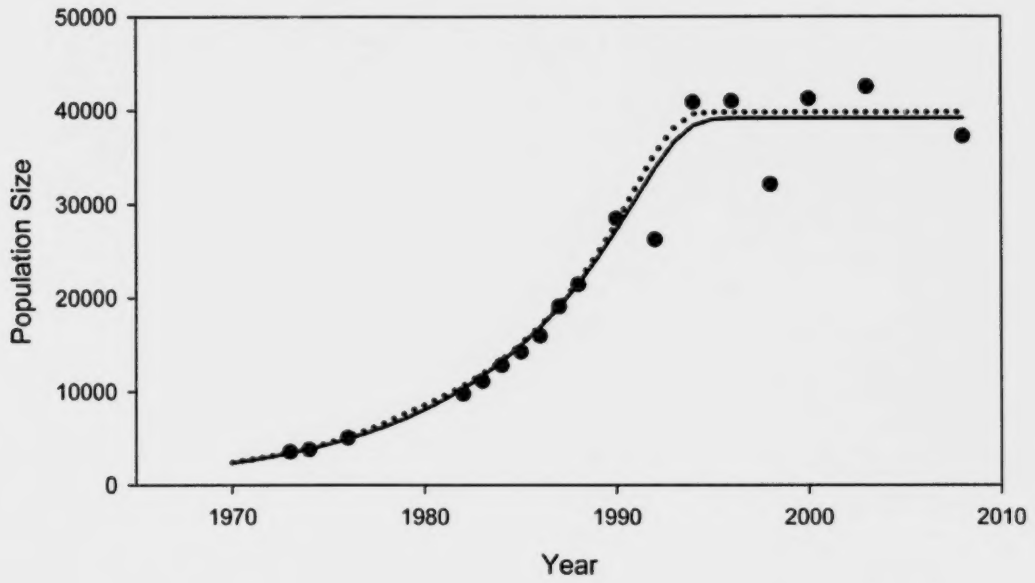

Figure 17. Population of harbour seals in the Strait of Georgia. The population increased from the 1970s to the mid-1990s, after the cessation of hunting, and has since stabilized (DFO, 2009 123). The dotted and solid lines represent two different model fits to the data.

Sightings of northern and southern resident killer whales occur frequently in the entranceways to the Strait of Georgia (e.g. Queen Charlotte, Johnstone and Juan de Fuca straits and lower Gulf Island areas), enabling researchers to keep track of whale populations. The populations of the northern and southern resident killer whales (*Orcinus orca*) increased between 1974 and the mid-1990s, when they began abruptly to decline (Ford, 2006; Ford *et al.*, 2005). By 2001, the northern and southern populations had declined by 8% and 17%, respectively (Ford *et al.*, 2009). Since 2001 the number of whales has increased again, although more gradually than it declined in the late 1990s (Ford *et al.*, 2009, Figure 18). The Northern and Southern populations of Resident killer whales are designated under *SARA* as Threatened and Endangered, respectively.

Resident killer whales eat salmon, but they are highly selective in their choice of prey. The southern resident killer whales that live in the Strait of Georgia eat Chinook salmon almost exclusively, even when sockeye are far more numerous (Heise, 2005). The mortality and birth rate of both the northern and southern residents is closely correlated with the abundance of Chinook salmon (Figure 19, Ford *et al.*, 2009). Killer whales are also threatened by increasing human disturbance, including boat traffic, and contaminants (Heise, 2005; Ross, 2006).

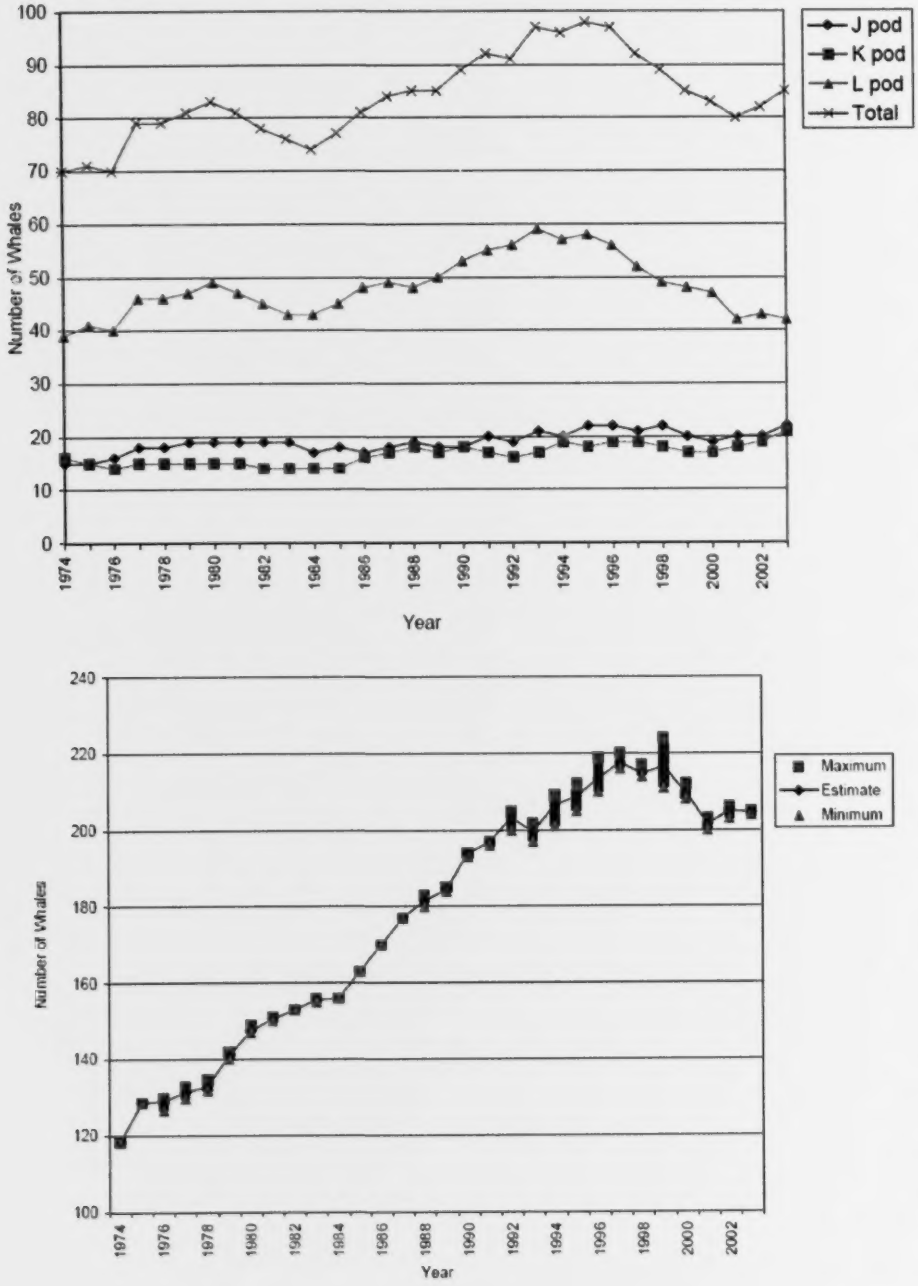

Figure 18. Population size and trends for (upper panel) southern resident and (lower panel) northern resident killer whales 1974-2003. Figure from DFO (2008).

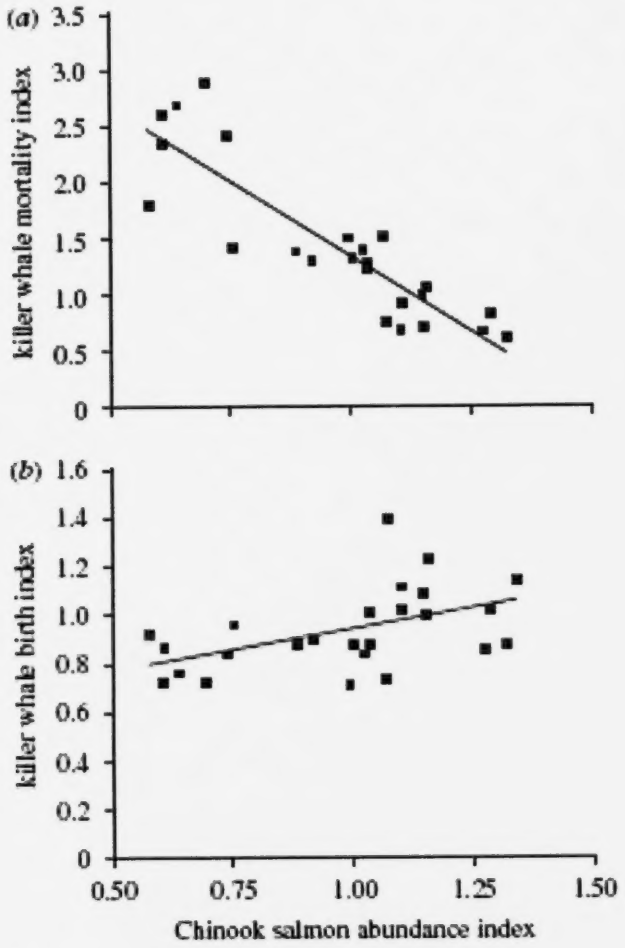

Figure 19. Correspondence between killer whale mortality/birth rate and Chinook abundance. (a) Mortality (r^2=0.78) and (b) birth indices (r^2=0.23) of northern and southern resident killer whales combined, as a function of coast-wide abundance indices for Chinook salmon over the period 1979–2003. Index values are expressed as 3-year running means and are lagged by 1 year after Chinook salmon abundance (Ford et al., 2009).

Because of their high trophic level, many marine mammals accumulate high concentrations of persistent contaminants, such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) (Grant and Ross, 2002; Ross *et al.*, 2000). Some live for decades and are unable to metabolize the contaminants, further increasing their burden (Hickie *et al.*, 2007). Even grey whales (*Eschrichtius robustus*), which feed at a much lower trophic level than killer whales, have developed high contaminant concentrations from the sediments that they filter (Ross *et al.*, 2007). The concentration of PCBs in Strait of Georgia killer whales easily surpasses the level known to cause immunotoxicity in harbour seals (Figure 20). The contaminant loads carried by marine mammals decrease once the discharge is reduced or eliminated, but the long life-span and high trophic level of marine mammals and their low ability to metabolize the persistent chemicals make the recovery slow (Ross *et al.*, 2007).

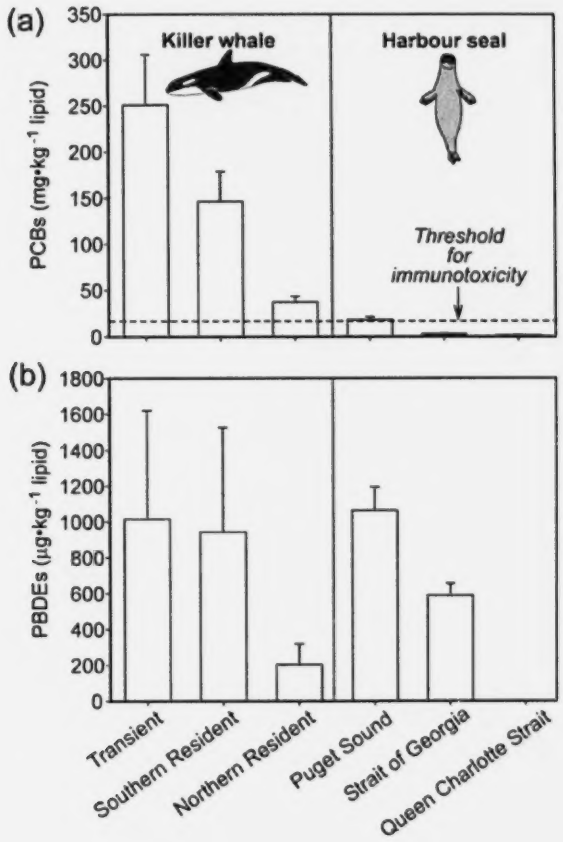

Figure 20. Concentrations of PCBs and PBDEs in several populations of killer whales and harbour seals (Ross et al., 2007). Of the killer whales, the main population in the Strait of Georgia is the "southern resident" group. Concentrations of PCBs are above the threshold known to cause immunotoxicity in harbour seals. The threshold concentration for PBDEs is not known.

9. MARINE BIRDS

Marine birds comprise shorebirds, seabirds and seaducks. Shorebirds, such as sandpipers (*Calidris sp.*) and plovers (*Charadrius sp.*), typically exploit the interface between land and water, foraging principally on intertidal invertebrates found on the surface or within substrates (Cramp and Simmons, 1983). They migrate widely from breeding areas in arctic and subarctic tundra to subtropical and tropical estuarine mudflat or mangrove ecosystems. Some species fly as far as southern South America to overwinter (Lanctot and Laredo, 1994; Parmelee, 1992). Along the way, shorebirds visit stop-over sites where they refuel for the next leg of their journey, and some species moult their feathers before reaching their wintering grounds. Migration is considered one of the riskiest phases of the shorebirds' annual cycle (Hockey *et al.*, 1998; Lank *et al.*, 2003; Summers *et al.*, 1995), and food availability during migration is critical not only to offset the metabolic costs of sustained flight but to reduce exposure to predation while refuelling (Lank *et al.*, 2003).

Global populations of many shorebird species are declining (O'Hara *et al.*, 2007). Widespread degradation and habitat loss at stop-over sites and on overwintering grounds may be the cause of these population declines, although this has not been shown conclusively for most shorebird species (Sherry and Holmes, 1996). Shorebird species generally express a high degree of fidelity to breeding, stop-over and wintering locations (Butler *et al.*, 2002; Gratto *et al.*, 1985; Holmes, 1971; Marks and Redmond, 1996; Middlemiss, 1961; Summers *et al.*, 1990; Warnock and Takekawa, 1996), so they cannot readily adapt to degradation of critical habitat by moving elsewhere. The mudflats associated with the Fraser River delta provide a crucial stop-over point for many species of shorebirds, and a number of migratory pathways converge there (Butler, 1994; Butler *et al.*, 1996). Urbanization of the shoreline threatens these birds, as does the potential loss of intertidal areas due to projected sea level rise, as described in the Loss of Coastal Habitat section.

Seabirds, such as alcids (auks (*Alle alle*), guillemots (*Uria aalge*), murres (*Uria sp.*) and murrelets (*Uria sp.*)), cormorants (*Phalacrocorax sp.*) and albatrosses (*Diomedea sp.*), spend most of their lives at sea, but come ashore to breed, typically in colonies on islands (Harrison, 1987). Marbled murrelets (*Brachyramphus marmoratus)* are unique among the seabird species, in that they breed in trees. Nests for this species have been found only in tall, trees with broad, moss covered-branches (Nelson, 1997). Such trees are mainly found in old-growth forests, which are increasingly rare in coastal British Columbia. In addition to habitat loss, sea birds are threatened by contaminants (e.g. Elliott, 2005). The populations of open-nested species, such as cormorants and gulls, may be further reduced by predation by the recovering bald eagle population (Gaston *et al.*, 2009a) Variations in gull population in this Ecozone cannot be interpreted simply to reflect changes in the marine ecosystem, since gulls feed extensively on anthropogenic sources, such as garbage and fisheries waste (Gaston *et al.*, 2009a; Gaston *et al.*, 2009b). In contrast to the general trend for seabirds, the Rhinoceros Auklet population has increased on some Gulf Islands, although the numbers are still very low (Gaston *et al.*, 2009a).

In addition to habitat loss, seabirds are sensitive to variations in oceanic productivity and the timing of the peak zooplankton biomass. Peak food requirements during chick rearing generally coincide with peak productivity in oceanic plankton communities near the colonies (i.e., "spring bloom"). A mismatch in timing or reduced productivity can lead to reproductive failure for that year (Gjerdrum *et al.*, 2003; Peterson *et al.*, 2006). If the zooplankton biomass in the Strait of Georgia continues to peak earlier in the year and the sea birds do not adapt, the birds may face extensive reproductive failures in the future. On the Pacific coast, two major oceanographic "regime shifts" are recognised during the period for which we have seabird records. These occurred in or about 1987 and 1998 and involved the degree of upwelling occurring in the California Current system. Repercussions for seabirds of decadal-scale variability and regime shifts have been documented extensively (Veit and Montececchi, 2006).

Sea ducks, like seabirds, spend much of their lives at sea but tend to stay close to shore. They typically breed inland around lakes, rivers and marshes (Cramp and Simmons, 1983). Although they are the least studied of the marine avifauna, several threats have been identified, including degradation of habitat in both breeding and wintering areas (i.e., marine coastal areas) (Board, 1988). Both sea ducks and seabirds are sensitive to oil slicks in water. There have not been any major oil spills in the Strait of Georgia, but aerial surveillance and beached bird surveys have shown that small spills (< 1000 L) are common, particularly along the shoreline of the Strait, and these small spills can harm seabirds (O'Hara *et al.*, 2009). The National Aerial Surveillance Program seems to have had a deterrent effect on the discharge of small amounts of oil from ships in the Strait of Georgia (O'Hara *et al.*, 2009).

10. LOSS OF COASTAL HABITAT

Fish, intertidal organisms, marine birds (see Marine birds section) and other species are threatened by the loss of coastal habitat (Levings and Thom, 1994). Building jetties, causeways, seawalls and other structures along the edge of the water and changing the course of rivers interferes with the natural movement of particles, resulting in erosion that endangers coastal communities and can cause beaches and mudflats to shrink. The construction of hard edges, including the extensive channelization of rivers, also hinders the migration of salmon upstream, because fish require quiet pools in which to rest along the way. It has been suggested that urbanization along river banks has been largely responsible for the decline in the population of Pacific salmon (Montgomery, 2003) over the last few hundred years.

The sockeye salmon stock of Sakinaw Lake on mainland British Columbia, east of Texada Island, for example, has decreased rapidly as a result of a modification in habitat (GBAP, 2006). The migration route was partially blocked by log storage near the outlet, and residential and recreational development along the shores of the lake has damaged spawning beaches. Between 1987 and 2002, the average number of adult spawners dropped from about 1000 per year to < 80. (GBAP, 2006)

Urbanization along the shores of the Strait of Georgia and of the rivers that flow into it has resulted in a dramatic reduction in usable habitat. Levings and Thom (1994) reported that all marshes and estuaries that they measured around the Strait of Georgia had lost area since the 1880s, although the percent lost varied widely from place to place (range: 0.8% at Little Qualicum to 92.9% Burrard Inlet; average loss 31.3%). In the Fraser estuary and lower river, the same period saw the loss of salt marshes, bogs, wet meadows and the Sumas flood plain lake, while there were gains in brackish and freshwater marshes due to mudflat accretion (Levings and Thom, 1994).

Climate change can interact with urbanization to accelerate the loss of habitat. Figure 21 shows the areas of the Lower Mainland that will be vulnerable to flooding as a result of a projected increase in global sea level combined with local delta subsidence (Shaw *et al.*, 1998). Mudflats and low-lying areas, such as the communities of Richmond and Coquitlam, are vulnerable to flooding.

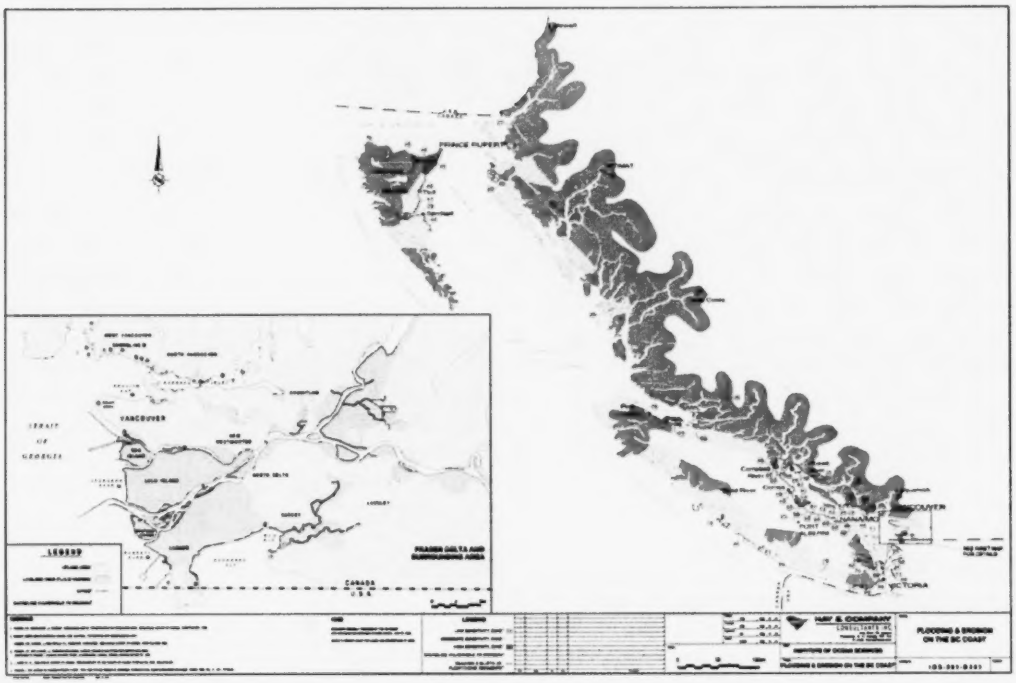

Figure 21 Sensitivity of B.C. coast to sea level rise. Red indicates areas of highest sensitivity (Shaw et al., 1998).

In the past, sea level rise has resulted in transgressions of the sea over land. Beaches and mudflats have simply moved inland. This time, however, water rising in the Strait of Georgia will meet dykes and other impervious structures around the lower mainland. Since a transgression that would turn the communities of Richmond and Coquitlam into mud flats will presumably be met with dykes and other protective measures, the water will likely rise up the sides of the walls, reducing or eliminating the intertidal mud flats around Vancouver. Those mud flats are critical habitat for many species, including shore birds, as described in the Marine Birds section.

11. CONTAMINANTS

Compared with other coastal seas around the world, the Strait of Georgia is still relatively unpolluted (Macdonald *et al.*, 2003) and supports abundant marine life. However, urbanization and agriculture along the shores of the Strait of Georgia and adjacent inlets has resulted in contamination by metals, organic pollutants, other chemicals and pathogens (See reviews by Harrison *et al.*, 1994; Macdonald and Crecelius, 1994; Waldichuk, 1983; West *et al.*, 1994). Chemical and biological pollution has led to temporary fisheries closures in Howe Sound in the past and to indefinite closures for shellfish harvesting around municipal outfalls. Chemical contaminants have been suggested as a cause of the disastrously early migration of late-run sockeye salmon up the Fraser River in the late 1990s and early 2000s (Johannessen and Ross, 2002). In addition, persistent, bioaccumulative, toxic chemicals have been listed as one of the three conservation threats to the Strait of Georgia's endangered killer whales (Heise, 2005; Ross, 2006). (See Marine Mammals section.)

Contaminants can be considered in two groups: those whose discharge and / or use has been banned or reduced, and those that are in current use. Discharges of dioxins, furans, PCBs, dichloro-diphenyl-trichloroethane (DDT) and tributyl tin, an anti-biofouling agent, were all limited following evidence of harm to marine organisms (e.g. Hagen *et al.*, 1997; Macdonald and Crecelius, 1994; Stewart and Thompson, 1994). Figure 22a shows a typical sediment core profile of PCBs, as a representative of the banned chemicals. The discharge of mercury from some businesses, such as dentists' offices, has also been limited by local source control programs, but there has been episodic mercury contamination locally, beginning with placer gold mining along the Fraser River in the 1860s (Johannessen *et al.*, 2005). Regulating chemicals to reduce their discharge has resulted in decreased concentrations in sediments and low trophic level biota, with the effect, in some cases, of permitting a closed fishery to re-open (e.g. dioxins in Howe Sound crabs, Yunker and Cretney, 1996)

Polybrominated diphenyl ethers (PBDEs), used primarily as flame retardants on household and commercial goods, provide an example of a persistent organic chemical in current use. Without regulation to reduce their discharge, the concentration of such chemicals increases in the environment (Figure 22b, Johannessen *et al.*, 2008a) and in organisms (Ikonomou *et al.*, 2006; Ross, 2006). All the commercial mixtures of PBDEs are now banned in Canada (as of 2009), following voluntary withdrawal of two of the formulations from the market, but the dominant mixture, known as deca-BDE, has been in ever-increasing use, and the discharge of deca-BDE into the environment will continue (and likely continue to increase) for deacdes, because of the very large reservoir on land in furniture, electronics, toys, etc. Deca-BDE largely drives the profile shown in Figure 22b. The flux of PBDEs into the Strait of Georgia will soon exceed that of PCBs (Johannessen *et al.*, 2008a). PBDEs are toxic and damage the thyroid, neurological and immune systems of exposed animals (Ross, 2006). There are many other chemicals in current use in the Georgia Basin that may have equally important biological effects, but which are only now beginning to be measured. Many pharmaceuticals are not measured at all, because techniques for their measurement have not been developed, but they are likely to be present in this environment.

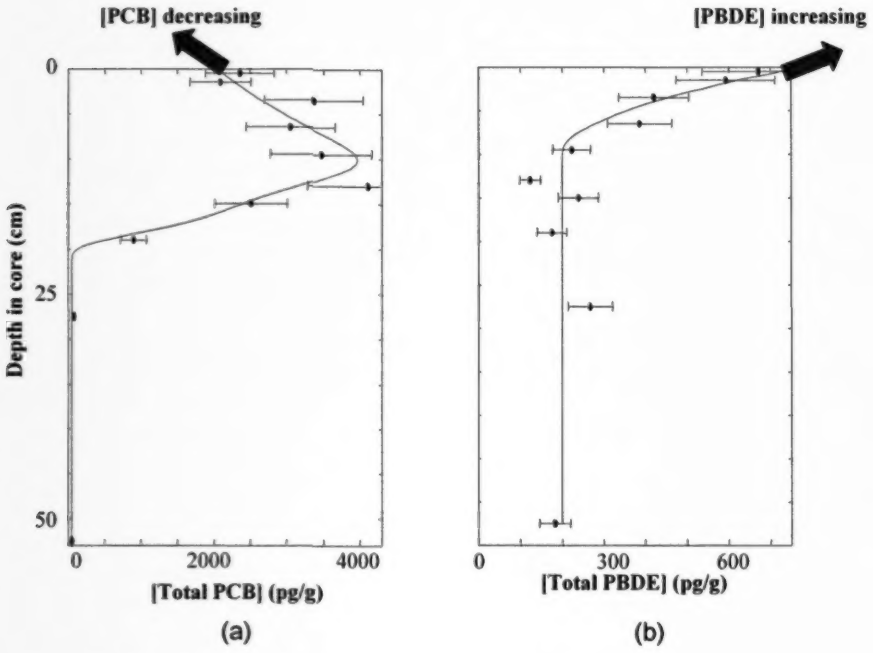

Figure 22. Sediment core profiles of (a) PCBs and (b) PBDEs as examples of banned and current use chemicals, respectively, from a core collected in the northern Strait of Georgia, west of Texada Island (Johannessen et al., 2008a). Since PCBs were banned in North America in the late 1970s, their concentration in sediments has decreased, while that of PBDEs, introduced locally in about 1978, is increasing rapidly. Sediment accumulation rates and mixing by benthic organisms affect the rate at which pollutants can be buried in sediments. Benthic mixing smears particles over a range of depths, so no depth on the y-axis corresponds to a discrete time horizon.

Unfortunately, marine mammals cannot recover as quickly as sediments or short-lived invertebrates. Marine mammals can have very long life-spans, and some chemicals are passed on to the young before birth and during nursing (e.g. Ross *et al.*, 2000). Southern resident killer whales in the Strait of Georgia, for example, are still highly contaminated with PCBs more than 30 years after PCBs were banned in North America (Figure 23). Local harbour seals are also still highly contaminated with PCBs, dioxins and furans from local and long-range sources (Ross *et al.*, 2004). Concentrations of PCBs are decreasing in harbour seals, while those of PBDEs are increasing rapidly (Peter Ross, unpublished data, September, 2009). The long-term effects of PBDEs, pesticides and pharmaceuticals on marine mammal health are largely unknown. (See Marine Mammals section for more information about contaminants in marine mammals.)

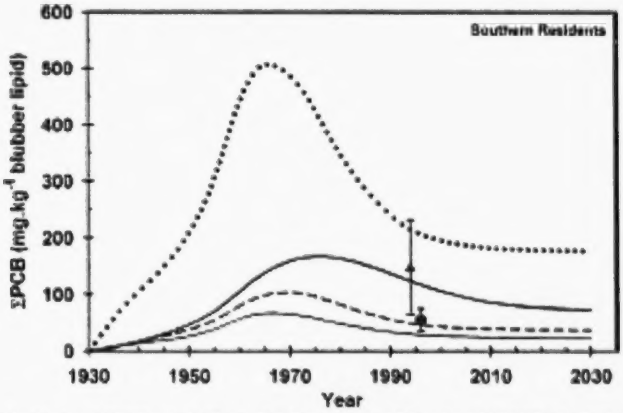

Figure 23. The concentration of PCBs in killer whales peaked in about 1970, but the concentration is still high, because these animals are long-lived and pass on persistent contaminants to their offspring at birth and during nursing. The temporal trends are based on a model that used estimated dietary exposure to PCBs. Mean measured PCB concentrations are shown for males (solid triangle) and females (solid circle) (Hickie et al., 2007).

In addition to chemicals, structural pollutants, such as lost fishing gear and plastic can threaten marine organisms. Plastic in the ocean is a global scale pollutant that harms marine mammals, sea birds and other organisms (e.g. Derraik, 2002). The effect of plastic has not been quantified systematically in the Strait of Georgia, but, it has resulted in numerous marine mammal strandings (Peter Ross, Fisheries and Oceans Canada, personal communication, July, 2008).

12. INVASIVE SPECIES

An invasive species is "a non-native species, whose introduction will likely cause (or has already caused) damage to the host ecosystem, existing species therein, the economy or human well-being" (DFO, 2007). Invasive species have the potential to change ecosystems through competition with native species, habitat modification, predation, hybridization and other mechanisms (Levings *et al.*, 2002). If introduced species do not cause measurable damage, from a human point of view, they are known as alien, rather than invasive, species. Alien and invasive species collectively are called non-native.

There are almost three times the number of non-native species in the Strait of Georgia as in other parts of coastal British Columbia (Levings *et al.*, 2002). Levings et al. (2002) reported 89 non-native species in the Strait of Georgia, comprising phytoplankton and macroalgae, invertebrates, fishes, birds and mammals. Gillespie (2007) reported 34 intertidal non-native species from the Strait of Georgia, compared with 15 or fewer for other areas of British Columbia. The concentration of aquaculture, estuarine circulation patterns and the increasingly intensive international shipping in the southern straits have likely contributed to the large number of non-native species (Gillespie, 2007; Levings *et al.*, 2002).

Sometimes non-native species are introduced deliberately, as in the case of eastern and Pacific oysters (*Crassostrea virginica and Crassostrea gigas*), which were imported into the Strait of Georgia for aquaculture in 1883 and 1912, respectively (Carlton and Mann, 1996; Quayle, 1988). The Pacific oyster now supports significant aquaculture and recreational fisheries, as well as a small, commercial, wild fishery. Other molluscs, including the Atlantic blue mussel,

Mytilus edulis, the Mediterranean mussel, *Mytilus galloprovincialis*, and the Japanese weathervane scallop, *Mizuhopecten yessoensis* were also introduced for aquaculture and have been hybridized with native species in the Strait of Georgia (Heath *et al.*, 1995). The hybridized mussels have established independent colonies, while the scallops are still confined to aquaculture sites.

More frequently, non-native species arrive unintentionally, in or on ships (solid ballast, ballast water, hull fouling), together with other introduced species or through the trade in live food and plants (Gillespie, 2007). At least ten species of molluscs and several other invertebrates and plants are thought to have arrived in company with the deliberately introduced species (Gillespie, 2007). The number of non-native species reported in the Strait of Georgia has increased 40-fold over the last century (Figure 24), although part of the reported increase may reflect increased awareness and surveillance or resolution of long-standing taxonomic issues.

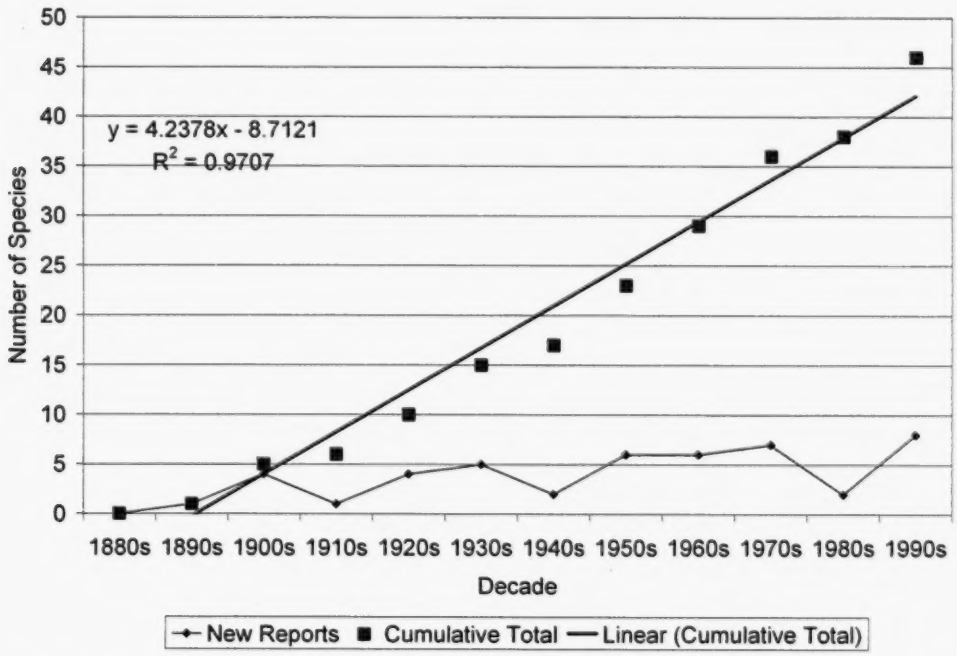

Figure 24. Cumulative reports of invasive species in the Strait of Georgia, adapted from Levings. (2002).

Eelgrass beds, aquaculture and native clams and crabs are all potentially at risk from invasive species, and there is some concern that if the predatory European green crab (*Carcinus maenas* Linnaeus) arrives in the Strait of Georgia, it will reduce the local crab and bivalve populations enough to damage those fisheries and significantly reduce the food available for marine birds (Jamieson *et al.*, 1998). Some species that have caused measurable damage elsewhere have been observed in the Strait of Georgia. For example, non-native, solitary and colonial tunicates that have been observed on the eastern side of the Strait of Georgia are considered to present a high ecological risk, as those species have damaged shellfish aquaculture on the east coast of Canada and in New Zealand (Therriault and Herborg, 2007). Spartina cordgrass, which modifies habitat, making it unsuitable for oysters and clams, has also reached the intertidal zone of the Strait of Georgia

(http://www.ducks.ca/province/bc/volunteer/spartina.html), although it seems still to be controllable by physical removal, rather than requiring the chemical methods employed to eliminate some very large meadows observed in Washington and Oregon (http://www.clr.pdx.edu/docs/SpartinaPlan5-8.pdf). Northward migrations of subtropical fishes may also create competition within existing habitat. Cheung et al. (2009) estimate that fish and invertebrates will be forced poleward at a rate of about 50 km per decade due to global warming. It is possible that much stronger northward migrations will occur due to expanding hypoxia along the California to Alaska coast (Frank Whitney, personal communication, 2009). To date there is no evidence of detrimental effects from invasive species in the Strait of Georgia (Levings *et al.*, 2002), partly because it is difficult to ascribe effects confidently to a particular invader. However, climate change, fishing and other factors discussed in this report may reduce the resistance of the native biota to threats from invasive species in the future.

13. SPECIES AT RISK

Twelve Georgia Basin marine species (Table 1) have received designation by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), and some of these are now legally listed under Canada's Species at Risk Act (SARA). These species are at risk due to a combination of factors, including habitat loss, pollution and fishing (discussed individually above).

Table 1. A list of marine invertebrates, fishes and mammals found in Strait of Georgia waters that have received a status classification under COSEWIC, some of which are also listed under SARA (adapted from SARA (2008)).

Grouping	Common name	Species	Legal listing under SARA	COSEWIC status
Invertebrate	Northern abalone	*Haliotis kamtschatkana*	yes	Endangered
Invertebrate	Olympia oyster	*Ostrea conchaphila*	yes	Special Concern
Fish	Bluntnose Sixgill Shark	*Hexanchus griseus*	no	Special Concern
Fish	Chinook salmon (interior BC spawners)	*Oncorhynchus tshawytscha*	no	Threatened
Fish	Coho salmon (interior B.C. spawners)	*Oncorhynchus kisutch*	no	Endangered
Fish	Green sturgeon	*Acipenser medirostris*	yes	Special Concern
Fish	Sockeye salmon (Cultus and Sakinaw Lakes)	*Oncorhynchus nerka*	no	Endangered
Mammal	Steller Sea Lion	*Eumetopias jubatus*	yes	Special Concern
Mammal	Harbour porpoise	*Phocoena phocoena*	yes	Special Concern
Mammal	Humpback whale	*Megaptera novaeangliae*	yes	Threatened
Mammal	Killer whale, northern resident	*Orcinus orca*	yes	Threatened
Mammal	Killer whale, southern resident	*Orcinus orca*	yes	Endangered

14. SUMMARY OF THREATS AND TRENDS IN THREATS

In a recent review of the effects of climate change and human activities of the ecosystem of the Strait of Georgia, Johannessen and Macdonald (2009) identified climate change, habitat destruction and fishing as the principal threats, both independently and in combination. Climate change will act through (1) sea level rise, flooding critical mudflat and beach habitats; (2) increased temperature of rivers, prohibiting the entry of salmon into spawning areas and favouring non-native species and parasites; (3) increased temperature of seawater, possibly changing the timing of the zooplankton bloom in the Strait and causing a timing mismatch between predators and prey; and (4) decreased oxygen and pH in deep waters, extirpating benthic species or at least narrowing the range of their distribution. Trends in these climate-related threats are discussed in sections 1-5 of this report.

Local human activities can act synergistically with the changes related to global climate (Johannessen and Macdonald, 2009). Habitat destruction is increasing, as a result of the rapidly-increasing human population of the Georgia Basin (pop. 4.1 million in 1976, 7 million in 2001, anticipated 9.1 million by 2025; US Environmental Protection Agency (2009), http://www.epa.gov/Region10/psgb/indicators/population_health/what/index.htm.) This occurs through development along coastlines, river banks and spawning beaches, channelization of rivers, discharge of contaminants into the freshwater and marine environments, and physical destruction of benthic habitat by trawling and other activities. See sections 10 and 11 of this report for more detail.

Fishing pressure varies from year to year, following the regulations of fisheries management and consumer demand. As has been demonstrated clearly in the case of the herring reduction fishery (1937-1967), reducing fishing pressure can allow stressed stocks to recover (Figure 14). See sections 6 and 7 of this report for more discussion of variations in and effects of various fisheries.

DATA GAPS

It was not possible to determine trends in all threats or in all potential ecosystem indicators because of limited data. For example, we lack a long time series of nutrient concentrations. Nutrient data were not collected systematically in the Strait of Georgia until 2002, although there were occasional nutrient measurements reported before that time.. Similarly, time series of pH have only begun this year (2009), and there is no time series of organic carbon measurements in the Strait from which we could deduce changes in oxygen utilization below the surface, although there is a one-year, quarterly record from 2003, which may act as a baseline in the future (Johannessen et al., 2008a). The changes in zooplankton biomass and composition, which may be critical to future change among fishes (and consequently marine mammals) are not well understood because of limited data. Those zooplankton trends which have been observed are alarming (e.g. Figures 7 & 8), however, and this topic should probably receive special attention.

We also lack time series of prey species for the piscivorous fishes and benthic organisms, because fisheries management in the past was based on assessments of fished species only. This lack impedes the assessment of both the reasons for the observed decline in piscivorous fish populations and any change in ecosystem structure which may be under way. The current Ecosystem Approach to fisheries management may help to fill this gap. Another limitation to the interpretation of time series of fish populations is that they tend to be based on landings of

commercial fishes rather than on estimates of pre-fishery biomass, and landings are affected by management and by market forces as well as by the actual number of fish present. We also lack trend data for marine mammals other than killer whales and harbour seals. Finally, habitat destruction does not seem to be monitored in a comprehensive way, which limits a broad understanding of the effects of urban development on the coastal marine ecosystem.

INTEGRATED ANALYSIS OF STRAIT OF GEORGIA STATUS AND TRENDS

The Strait of Georgia is changing, due to global climate change, local human activities and the interaction of the two. The Strait is already warming at all depths, and the concentration of oxygen in deep water is decreasing, partly as a result of the warming (Section 3 above). To date, the deep waters of the Strait have not gone anoxic, but the concentration of oxygen is already low and decreasing every year. If an anoxic zone develops at depth outside the Strait, as has occurred near California, the anoxic water could be upwelled and fill the deep basins of the Strait during a deep water renewal event. Hypoxic/anoxic events have likely occurred in the closely connected Howe Sound in the past (e.g. Leys *et al.*, 2004). Anoxic water is immediately toxic to fish and other creatures that require oxygen. The summer temperature of the Fraser River has increased, frequently approaching the threshold temperature of 21°C, at which salmon migration stops. Elevated seawater temperature also favours the reproduction and survival of some non-native species, such as American shad, and parasites, such as sea lice.

A change in the timing of the Fraser River freshet might affect the timing of spring phytoplankton production, although there is as yet no discernable trend in primary production, which experiences large interannual variability and short spikes throughout the growing season. Despite the interannual variability in the timing of the phytoplankton growth, the zooplankton biomass peak is shifting unequivocally earlier every year. In addition, the zooplankton biomass is decreasing and shifting toward an assemblage that is thought to be less nutritious for fish. These changes in zooplankton biomass and timing have caused reproductive failures among some species of marine birds, and there is speculation that juvenile fish may not be able to adapt or modify behaviour to match changes in zooplankton quantity, distribution or nutritional quality. To date there is no definitive evidence of such effects on Strait of Georgia planktivorous fish, other than declines in growth of some species. Recent declines in size-at-age could still be within the range of normal variability. Unfortunately, the large interannual variability in the populations of planktivorous fishes limits our ability to recognize a real downward trend until it has continued for a decade or more. Some small, local populations, however, have shown measurable trends with reasonable certainty, as in the decline of the Fraser River eulachon. Having to rely heavily on records of landings, which are partly driven by market forces and regulations, contributes to the difficulty in identifying real changes in fish populations.

The populations of many piscivorous fishes, including coho and Chinook salmon, are declining, while those of some planktivorous fish, including hake, chum and pink salmon, are generally stable or within normal ranges of historical variability. In general, resident fish appear to be declining more quickly than migratory fish. There may be a timing mismatch between large, piscivorous fish and their smaller prey, driven by climate change, that does not immediately affect the planktivorous fish. Contaminants might also contribute to the difference, since piscivorous fish are one trophic level above planktivorous fish, and the tissue concentrations of some contaminants increase with each trophic step (e.g. Ross *et al.*, 2000). Alternatively, or possibly in concert with climate effects, fishing may be preferentially removing larger (hence more piscivorous) fish. Fishing and hunting have certainly been responsible for population declines among fish and marine mammals in the past and in other areas of the world. The

population of harbour seals, for example, is now about ten times what it was in 1973, and this change is attributed almost entirely to the cessation of hunting.

Overharvesting has likely reduced the resilience of fish and other marine species. Archaeological and historical evidence suggests that the current populations of fish, whether increasing, decreasing or stable, represent only a small fraction of the abundance that existed on this coast a few hundred years ago, before European contact and the beginning of commercial fishing (Hebda and Frederick, 1990).

In addition to fishing, habitat loss and pollution also make ecosystems less resilient to the effects of climate change. While there may be little we can do locally to address some global-scale forcings, addressing local stressors can be effective. Environmental and tissue concentrations of contaminants have in many cases decreased once the discharge was eliminated. In the Strait of Georgia, the sediments and biota have recovered or begun to recover from contamination by dioxins, furans, tributyl tin, mercury and PCBs. The recovery in sediments and associated benthic organisms can be measured over a time scale of years, due to the large supply of inorganic sediment from the Fraser and other rivers, while recovery takes longer (decades) in longer-lived marine mammals, such as killer whales. Habitat restoration has been demonstrably effective in facilitating the recovery of some salmon stocks, and the population of herring has recovered from repeated crashes, after new harvest rules or closures reduced the fishing pressure (Figure 14).

The ecosystem of the Strait of Georgia has shown resilience in the past, having recovered from numerous past stressors and climatic variations. However, accelerating climate change is now combined with urbanization and fishing pressure. We do not know how the ecosystem will respond to the cumulative effects of human- and climate-driven changes in the future.

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